Chapter 20
Modern Technologies of Biomass Combustion and Pre-treatment for more Efficient Electricity Production: Review and Case Analysis

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Abstract Biomass combustion and biomass–coal cofiring represents a near-term, low-risk, low-cost, sustainable, renewable energy option that offers reduction in effective CO_2 emissions, reduction in SO_x and NO_x emissions. However, untreated, woody biomass has a relatively low energy density, low bulk density, high moisture content and is difficult to comminute into small particles. As a matter of fact, these properties make biomass preparation and conversion to electricity expensive. Moreover, biomass can absorb moisture during storage and may rot as well. These properties have negative impacts during energy conversion such as lower combustion and electricity generation efficiencies. Therefore, enhancement of biomass properties is advisable not only to improve its inferior characteristics, but also to make it a suitable alternative to fossil fuels. In order to address these problems, biomass is required to be pretreated to improve its quality.

Keywords Volumetric combustion · ROFA · Biomass · Biomass pre-treatment

Short Introduction

Although biomass coal has many advantages and much potential as a renewable-energy option (reduction in CO_2, SO_x and NO_x emissions), there are still many inconveniences attached to its usage. For this reason, there is a need to study more in detail how to overcome those issues. As the price of fossil fuels is going to increase and their availability on the market decrease, modern power plants must now use different coals, biomass or even waste fuel. Thus, modern combustion processes must be fuel flexible and must be able to accommodate changing fuel supplies.

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Introduction

At present very well known and established combustion technologies are used to burn fossil fuels. For example, combustion technology to burn coal was the subject of more than a hundred years of development. Coal, depending on its properties and quality, can be burned efficiently using well-known technologies: grate combustion technology, fluidised-bed combustion technology and pulverised-fuel combustion technology. Using already well-known, in-furnace combustion techniques it is possible to make combustion complete (low CO, low LOI) and clean (low NO_x combustion, in-furnace SO_x reduction) as well as maintaining the boiler's very high efficiency. Using end-of-tubes reduction methods, it is possible to obtain even lower emissions of NO_x and of So_x, as well as maintaining very low emissions of dusts. These technologies developed for coal are now used to burn biomass. Since biomass has very different properties from coal, there are many differences in the physics and chemistry of coal and biomass combustion. The main differences between biomass and coal which influence the combustion process and boiler performance are:

- the higher calorific value of coal comparing to biomass,
- the higher content of volatiles in biomass comparing to coal,
- the higher content of alkali metals and chlorine in biomass resulting in a higher risk of slagging,
- higher corrosion when burning biomass.

Consequently, there are the following technical problems to be solved when boilers designed to burn coal are to be used to burn biomass:

- combustion process modernisation,
- anti-slagging, anti-fouling and anti-corrosion measures,
- fuel preparation and fuel pretreatment.

Depending on the combustion technology, different solutions are applied. This work focuses on the technology of pulverised and dried biomass combustion. Fluidised-bed combustion of wet biomass is not discussed in this work. The main reason for this decision is the fact that the combustion of dry, pulverised biomass is of a higher efficiency, and, in the case of conversion from coal to biomass, improves chances of achieving the same capacity from the boiler.

Combustion Process Modernisation

Although there are many ways to modify a combustion process, there are only a few which modify the combustion process and can still guarantee minimum emissions, complete combustion, maximum boiler efficiency, and low operational and maintenance costs. Modern power plants must now use different coals, biomass or even waste fuel. Thus, modern combustion processes must be fuel flexible and must be able to accommodate changing fuel supplies. It has also to be able to utilise difficult fuels and reduce the negative effects of fuel blends by enabling direct, large percentage co-firing and a 100 % fuel switch. Traditional air-staging systems are not uncommon in utility and district-heating boilers, independent of firing configuration or combustion technology. However, the ability of traditional systems to accommodate different fuels and NO_x reduction for is limited. The typical organisation of staged combustion is shown in Fig. 20.1. In order to prevent the formation of nitrogen oxides from fuel-bound nitrogen, the primary combustion zone is operated under sub-stoichiometric conditions with excess air number (λ) less than one. To complete combustion, a secondary air is introduced into the upper furnace by means of an air supply system called Over-Fire Air (OFA). The secondary combustion zone is operated with excess air number (λ) above one. Interaction between the two separated combustion zones is difficult to control in large scale combustion chambers particularly when the boiler's load and operational parameters change. Negative effects of such staged combustion can be seen clearly when large percentage co-firing (above 40 % of coal replaced by renewable fuels) or 100 % fuel switch are introduced. Common negative effects of biomass combustion are:

- incomplete combustion (CO, unburned volatiles, carbon in fly and bottom ash),
- wrong temperature distribution along the height of boiler's combustion chamber (thus too high a use of spray water),
- slagging, corrosion and wastage of water walls inside the boiler's combustion chamber, as well as the steam preheater,
- dropin steam temperature and steam production rate, resulting in a reduction of boiler capacity of up to 20 %.

ROFA (Rotating Opposed Fired Air) (Moberg et al. 1999; Crilley et al. 2004; Higgins et al. 2010) is a boosted over-fire air system that includes a patented rotation process. With ROFA, the gas in the furnace is set in rotation via special asymmetrically placed, high velocity air nozzles. ROFA promotes intensive internal recirculation of flue gases from the level of secondary air injection, down to the primary combustion zone. This is particularly important when burning biomass

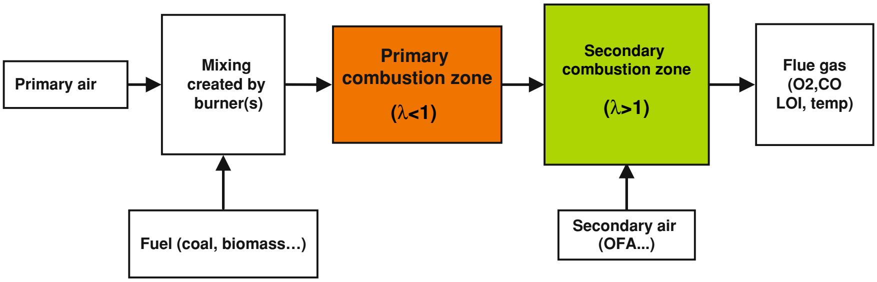

Fig. 20.1 Conventional staged combustion concept

with a high content of volatiles. Combination of air staging and internal flue gas recirculation changes not only in-furnace flow, but also affects combustion.

Due to intensive recirculation and good mixing between secondary air and flue gas, the combustion volume is larger than with conventional staged combustion. Such combustion is termed a Volumetric Combustion System (Fig. 20.2). With ROFA, volumetric combustion is created by very intensive mixing and recirculation of hot, reacting flue gases. Volumetric combustion is stabilised by the uniform temperature of the circulating flow field. The main advantage of applying this type of combustion is a very deep air staging and consequently a reduction in the formation of nitrogen oxides (NO_x), (Higgins et al. 2010). With ROFA the flue gas is well mixed with the available air in the entire upper furnace. This improves particle burnout and volatiles burnout. ROFA also increases particle residence time by changing their trajectories to utilise more of the volume of the furnace, thus reducing carbon content in the fly ash (LOI). The highly turbulent mixing and rotation prevent the formation of stratified flow, which enables the entire furnace volume to be used more effectively for the combustion process. Existence of the stratified flow, called also a "chimney" flow is a common phenomenon in the case of conventional air staging. It is often accompanied by non-uniform, and too high a temperature and CO concentration at the upper furnace outlet. Application of volumetric combustion changes the flow pattern of flue gases and eliminates these negative effects. More efficient mixing of the combustion air can also reduce the need for surplus excess air and also reduces CO emissions.

Slagging, Fouling and Corosion

Negative consequences of co-firing coal with biomass have already been reported in literature. Ash-forming elements like potassium, sodium, calcium, magnesium, silicon and aluminium are present in biomass and can cause slagging, fouling and high temperature corrosion. Mixing of ash from two fuels during direct co-firing enhances the negative effects because of the typically lower ash melting temperature of biomass ash.

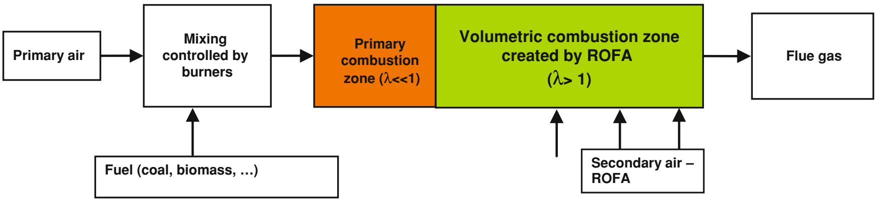
Primary air
Mixing controlled by burners
Primary combustion zone (λ<<1)
Volumetric combustion zone created by ROFA (λ> 1)
Flue gas
Fuel (coal, biomass, ...)
Secondary air – ROFA

Fig. 20.2 ROFA influence on the staged combustion process creating the volumetric combustion system

Mixing of biomass ash with coal ash can negatively influence the performance of the electrostatic precipitator and can cause deactivation of the SCR (Selective Catalytic Reduction) catalysts used for nitrogen oxide reduction.

Mixing of ash can create problems with the ash used by the cement and building industry. High alkali and/or chlorine content can lead to excessive ash deposition and can cause corrosion of heat-transfer surfaces as well as flue-gas cleaning equipment. At lower percentages of co-firing, there are no major problems related to slagging, fouling, or corrosion. However, there are problems at a high percentage of co-firing, or when 100 % biomass is fired. Substantial deposits of fly ash on heat-transfer furnaces are often observed, and an example of this is shown in Fig. 20.3. Deposits in the lower part of furnace (around the burners) and in the upper part of the furnaceare also often a problem. Ash distributed uniformly is quite easy to remove, but requires more frequent use of so-called soot blowers. Thickness of deposition on walls can be between 5 and 30 mm. At the superheater, the thickness of ash deposits can be between 15 and 50 mm (Fig. 20.3).

Removal of chlorides is a way to avoid these negative effects and to protect heat-transfer surfaces. After the installation of a volumetric combustion zone, the application of a chemical-injection system allows for the efficient and cost-effective reduction in this problem. Ammonium sulfate, $(NH_4)_2SO_4$ reduces the KCl levels in the flue gas and consequently reduces the level of deposits and rate of corrosion of the heat-transfer surfaces which fire the biomass. Roughly 80 % of the potassium chloride, KCl, is converted into the much less corrosive potassium sulfate, K_2SO_4.

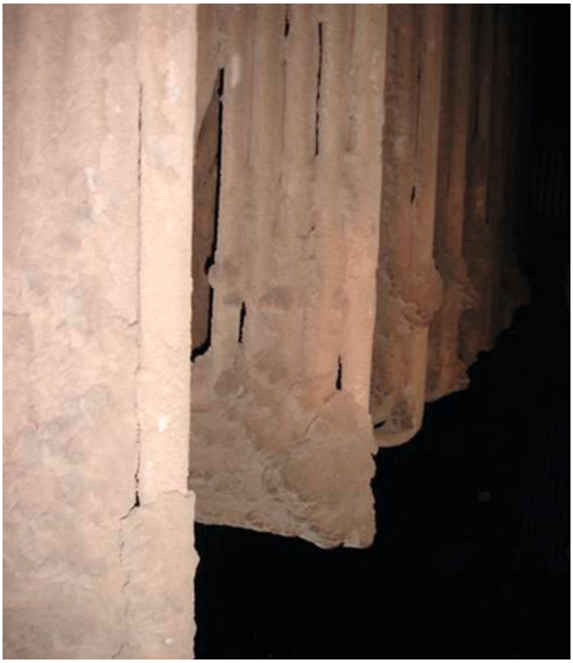

Fig. 20.3 Photo of superheater with deposits accumulated as a result of biomass combustion

Conventional Cofiring and Biomass Preparation Systems

Forced by new European Community legislation to reduce emissions, many power plants now plan to burn biomass, instead of coal, to produce electricity. There are few big boilers in the order of 200 MWel capacity where 100 % fuel switch from coal to biomass is going to be introduced. Some smaller boilers (in the order of 50–70 MWel capacity) are already fully converted from coal to biomass. However, the most common way of burning biomass is still the co-firing of coal with biomass. Here are the types of cofiring:

- Low percentage co-firing is when a maximum of 10 % of coal (by energy fraction) is replaced by biomass,
- Intermediate percentage co-firing is when up to 40 % of coal is replaced by biomass,
- Large percentage co-firing is when more than 40 % of coal is replaced by biomass.

In the case of low percentage co-firing, only a few percent of dry biomass (max. 10 %) is burned together with the coal. Raw biomass is mixed with coal before it is fed into the existing coal mills. Existing coal mills dry and pulverise biomass together with coal, producing a pulverised coal-biomass mixture. This mixture is burned in existing boilers without any substantial modernisation of the combustion system or of the boiler itself. Low percentage co-firing is used mainly because of the very low investment cost and high profit when burning biomass. Existing boilers are able to accommodate this coal-biomass mixture without any serious modernisation of the combustion system. There were some safety problems with milling biomass together with coal. However, after a few years of adaptation of coal mills to low percentage co-firing was carried out. At present, this rather safe, reliable operation is possible with a satisfactory rate of distribution of the coal-biomass mixture.

Intermediate percentage co-firing (up to 40 %) requires feeding the pulverised, dry biomass directly into the boiler's combustion chamber. Biomass is injected via separate nozzles or via burners. The number of nozzles, as well as their location, depends on the amount of biomass and its properties, but mainly on the combustion system used. Biomass can also be injected via new biomass burners or via existing, modified coal burners (dual fuel burners). Intermediate percentage co-firing requires a much greater modification of the air combustion system and some modification of the heat-transfer surfaces.

Large percentage co-firing, as well as complete fuel switch, (Blasiak et al. 2007, Blasiak 2008; Higgins et al. 2009) also requires feeding the pulverised, dry biomass through modified burners. Coal burners must be modified to handle higher mass-flow rates of fuel, and to guarantee complete, stable combustion throughout the operation. Full modernisation of the combustion system is necessary if the same capacity and steam parameters are to be kept. This would include, for example, the application of volumetric combustion, as well as substantial modernisation of the boiler heat transfer surfaces.

Biomass has a higher volatile content than coal, creating potential for a combustible environment. Therefore, the handling and processing of dry biomass must be performed safely. To ensure plant safety and operational reliability, the biomass handling system has to be designed to avoid and eliminate possible combustion during biomass storage, transport, and in the milling systems. The standard dry-biomass feeding system [*Wroclaw paper*] is comprised of the following main components:

- a biomass conveyance line from the fuel yard,
- a biomass (pellet, wood chips…) storage silo,
- hammer mills,
- dust separation cyclone filters,
- a powder silo,
- a biomass injection system (nozzles or burners).

Dimensions of the feeding system, (size and number of biomass storage silos, number of hammer mills, size of filters, size of powder silo, size and number of burners) and thus also the amount of investment necessary, depends on the capacity of the boiler and the amount of biomass replacing coal.

Conventional biomass feeding systems are commonly used although there are well known problems and disadvantages. The main problem is that even dried biomass has a relatively low energy density, low bulk density and is difficult to comminute into small particles. Moreover, it can absorb moisture during storage and may rot as well. This makes biomass transportation unsustainable and very expensive, as well as the negative impacts it can have during energy conversion, for example, lowering combustion efficiency. Therefore, enhancement of these properties is advisable to achieve the following benefits:

- reduced fuel transportation costs,
- reduced operational costs of fuel preparation and milling,
- an improved combustion process and boiler efficiency,
- reduced risk of slagging, fouling and corrosion, thus decreasing the boiler's downtime,
- reduced investment costs into the fuel-feeding system.

Biomass Pretreatmant Technologies

To achieve the benefits listed above, biomass must be pretreated to have a higher calorific value, grindibility and resistance to moisture. In recent times, the wood pellet industry has experienced rapid expansion into the energy market. Global wood-pellet production in the year 2009 was 13 and 8 million tons/year of this was consumed by European countries. It is predicted by the European Biomass Association that a consumption of 50 million tons/year will be reached in European countries by 2020. However, conventional wood pellets present problems such as low hardness, low specific weight, high sensitivity to moisture and low heat content. Moreover, the cost of transport is considered to play an important role in the wood pellet industry. Biomass is improved density can save transport and handling costs. Therefore, the improvement of wood-pellet quality, both in terms of fuel quality and density, seems indispensable. Currently, different approaches have been considered to improve the quality of the wood pellet, for example, torrefaction and fast pyrolysis. Another promising technology is the steam-explosion pretreatment process. Previously, application of the biomass steam-explosion process was limited to ethanol, and composite panel production. Both concepts are applied together with pelletisation of pretreated biomass to reduce transportation costs and the risk of explosion.

Recently, this concept has been brought into the spotlight to improve wood pellets, in order to produce high quality and high density pellets called "black pellets" as a biomass fuel to replace fossil fuels like coal and oil.

Steam Explosion

Woody biomass is made of cell wall with polysaccharides (cellulose and hemicelluloses) and an aromatic polymer named lignin. Cellulose and hemicelluloses are considered to be strongly bonded with lignin in wood. In the steam-explosion process, saturated steam ranging from 453 to 513 K in temperature is used to disrupt different components of biomass. The steam-explosion process involves the separation of the main components of woody biomass (lignin, cellulose and hemicelluloses) by both chemical degradation and mechanical deformation. The process involves adiabatic expansion of water inside the pores of the wood tissue and the auto hydrolysis of cell components. The steam-explosion pretreatment process can be divided into three different sub-steps. Initially, biomass is fed into the reactor and the vessel pressurised with steam until the desirable pressure and temperature are reached. Afterwards, sudden decompression is achieved by releasing pressure from the reactor. Later on, the slurry produced is passed through a filtration unit to separate the solids from the liquids.

Steam explosion pretreatment is striking in the context of the alteration of the elementary composition of fuel. A greater degree of carbonisation and the removal of oxygenated compounds leads to an increase in the heat content of the fuel. Moreover, the total amount of ash is also reduced in the residue from pretreated biomass. The removal of ash content can be attributed to the combination of water leaching and the disrupted cell structure. Although steam pretreatment shows promising results in terms of reducing the alkali and heavy metal components of biomass, degradation in ash fusibility was observed in the residue from steam-treated biomass.

Pellets produced from steam treated residue showed an increment in certain physical properties of the pellets such as density, impact resistance, and abrasive resistance. The higher density of the pellets can be attributed to the greater proportion of fine particles produced during the process. On the other hand, higher impact and abrasive resistance can be attributed to the melting of lignin, which has a low molecular weight, on the surface of the pellets during pelletisation (Sassner 2006).

Biomass Torrefaction

Torrefaction (Bergman and Kiel 2005; Bergman et al. 2005) is a thermal pretreatment process applied to enhance the quality of biomass fuel. In process of torrefaction, numerous products are formed, such as a solid and some liquids and gases. The solid is rich in carbon in comparison with oxygen. As a result, a significant improvement in the heat content of the biomass (solid) can be achieved (20–23 MJ/kg). The heating value of torrefaction gas can vary from 5.3 to 16.2 MJ/Nm^3. Therefore, torrefaction gas can be combusted to generate heat. Although the torrefaction process has been validated in the laboratory and on the scale of a pilot, there are many issues that need to be addressed before it can be used on a commercial scale. These include safety issues, fouling and corrosion when using it in co-firing. In addition, the choice of an appropriate reactor for torrefaction is considered decisive in plant performance.

Several reactor technologies are available nowadays. With the choice of appropriate technology, torrefaction can be proven beneficial for biomass chain supply. It is expected that the torrefaction process will provide an important contribution to biomass chain supply in the near future. The concept of the torrefaction process is shown in Fig. 20.4 (Biswas and Yang 2011). Initially, wet biomass is dried in a dryer with flue gas to reach the desired moisture content: to 10 % from 20 %. The drying temperature is 135 °C to provide sufficient energy for drying and avoiding saturation of the gases and volatilisation of the biomass. The dried biomass is torrefied under certain process conditions by using a majority of torrefaction gas. The reason for using torrefied gas is to ensure an inert atmosphere for the torrefaction process. Torrefaction gas is used as the main source of energy for the process. If the process requires additional energy, due to higher moisture content, part of the torrefied biomass is used as an energy source.

Biomass type has a significant effect on product yield, the energy retained in product (Fig. 20.5) and the efficiency of the torrefaction process (Fig. 20.6). Softwood tends to provide higher process efficiency in comparison with hardwood and agricultural residue. On the other hand, the choice of process conditions has great importance when considering process efficiency. Extreme process conditions may lead to excessive loss of mass and hence reduction in the efficiency of the process. Therefore, it is advisable to operate the process under less severe conditions, i.e. below auto-thermal point, to maximize process efficiency. Although

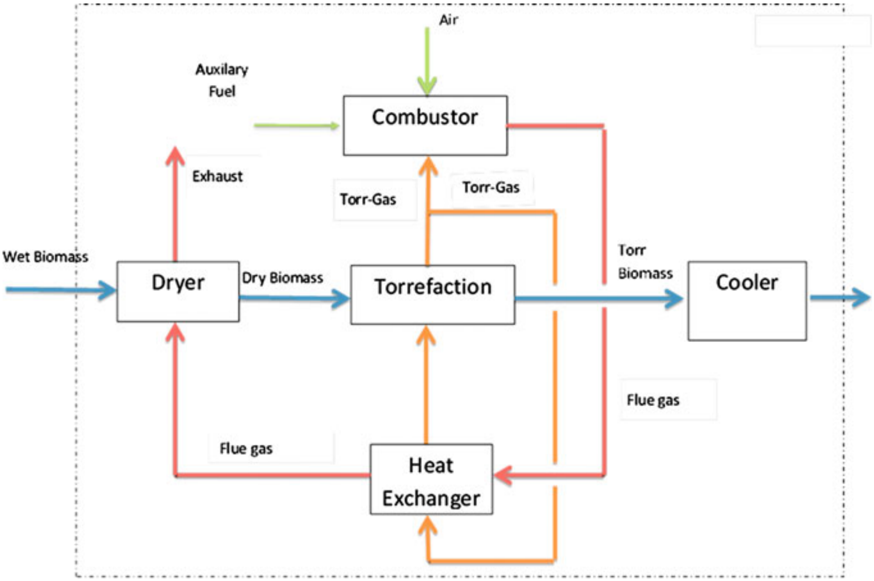

Fig. 20.4 Process flow diagram for the torrefaction process

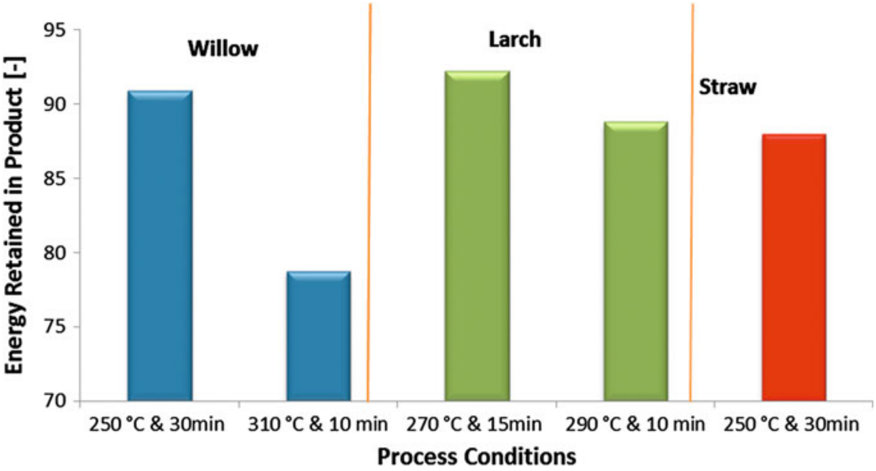

Fig. 20.5 Energy retained in product (torrefied biomass) after the torrefaction process versus the process conditions

process efficiency is observed to be around 80–90 %, it can be significantly improved by recovering heat from the cooling water used for the solid, which can be used as preheated water for district heating systems. Therefore, desirable process performance can be achieved by the correct choice of biomass, process conditions and an effective way of using the low quality heat of the system

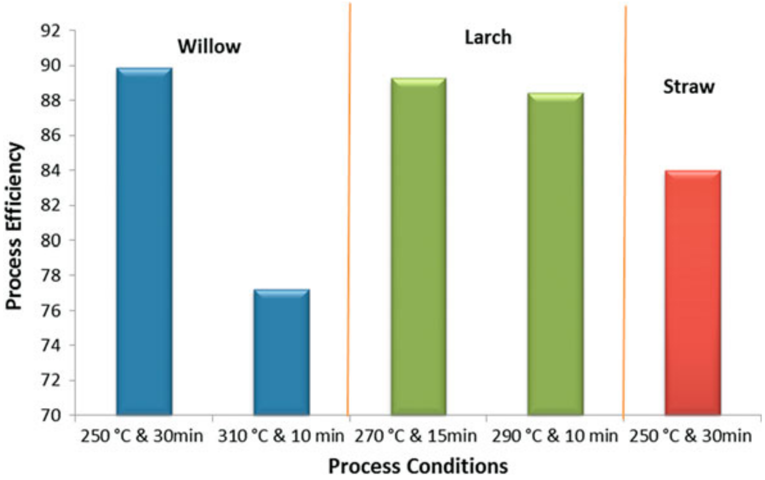

Fig. 20.6 Overall torrefaction process efficiency versus the process conditions

Influence of Biomass Pretreatment on Boiler Modernisation

It is a known and common practice, that even moderate percentage co-firing of pulverised, dried biomass requires modification of the air-supply system in order to secure better mixing inside the combustion chamber. The combustion of pulverised, torrefied biomass also requires the modernisation of the combustion process and combustion air-supply system. It is particularly necessary when large-percentage co-firing of torrefied biomass and coal, or a complete fuel switch, is to be performed. Applying conventional combustion technologies in such cases will encounter such difficulties as a fall in boiler efficiency, reduced steam production, a drop in steam parameters, increased fouling and corrosion of heat transfer surfaces inside the boiler.

Biomass, as well as torrefied biomass, has a much higher content of volatiles. A large fraction of torrefied biomass is released as volatiles (up to 65–75 % of mass) therefore gas-phase temperature distribution will be different compared to that of pulverised coal combustion or standard biomass. Modified combustion systems must be flexible and secure complete and clean combustion of volatiles, as well as particulates, but also must secure the performance of the boiler; that is the same steam flow rate and steam parameters.

It is known that the change from coal to co-firing significantly influences temperature distribution along the height of the boiler. When firing coal, the area of highest temperature is located just above the burner zone. When co-firing, there are two zones of high temperature: one zone just above the burners and a second zone much higher in the upper furnace. The reason for this bi-modal temperature distribution is a lack of good mixing. In order to improve and control the temperature in the upper furnace, and at the inlet to the superheater, much better mixing must be introduced.

The highly turbulent mixing and rotation prevent the formation of stratified flow, which enables the entire furnace volume to be used more effectively for the combustion process. Existence of the stratified flow, called also a "chimney" flow, is a common phenomenon in conventional boilers. It is often accompanied by a non-uniform and too high a temperature and CO concentration at the upper furnace outlet.

Figure 20.7 shows temperature distribution in a vertical cross-section of a steam utility boiler fired with different pulverised fuels. In all three cases the firing capacity is the same, as well as having a similar size distribution. The combustion system used is the same as that traditionally used for the combustion of pulverised coal. It can be easily observed that torrefied biomass with the same calorific value as bituminous coal creates a much higher temperature at superheater level. In the case of this combustion process and a fuel switch from coal to torrefied biomass, the boiler will not work properly. Therefore, the above mentioned modernisation of the air supply system, as well as the introduction of much intensive mixing, seems necessary.

Application of a proper air supply and mixing system will result in much more uniform temperature distribution, complete combustion, better operation, boiler load flexibility and better steam parameters. Because of better mixing, modification of burners is often not required and existing burners can be used to burn pulverised coal or pulverised, torrefied biomass with good flame stability.

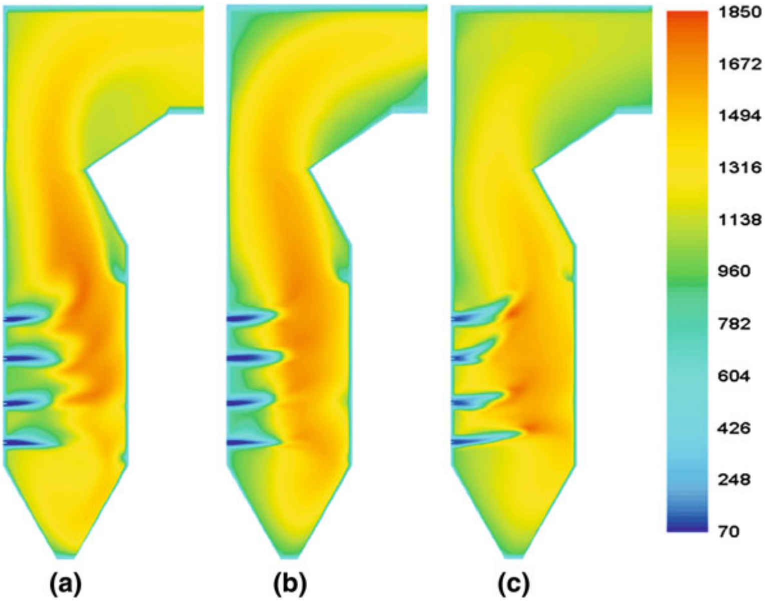

Fig. 20.7 Temperature distribution in a vertical cross-section of a steam boiler fired with pulverised **a** torrefied biomass no. 1, **b** torrefied biomass no. 2, **c** bituminous coal

Because of differences in the chemical composition of biomass and the coal-firing system, boiler modifications and equipment additions are also required. Extra heat transfer surfaces at convective part of the boiler must be analysed and, most probably, additionally installed when 100 % of torrefied biomass is fired. This decision must, of course, be based on the thermal calculations of the boiler.

Slagging, Fouling and Corrosion When Firing Torrefied Biomass

Negative consequences of co-firing coal with biomass have already been reported in literature. Ash-forming elements like potassium, sodium, calcium, magnesium, silicon and aluminium are present in biomass and can cause slagging, fouling, and high temperature corrosion. Mixing of ash from two fuels during direct co-firing enhances the negative effects because of the typically lower ash-melting temperature for biomass ash. Mixing of biomass ash with coal ash can negatively influence the performance of the electrostatic precipitator and can cause deactivation of the SCR catalysts used for nitrogen oxide reduction. Mixing of ash can create problems with the ash used by the cement and building industry. High alkali or chlorine content can lead to excessive ash deposits and can cause corrosion of heat transfer surfaces, as well as of flue gas cleaning equipment. In order to avoid all these negative effects, an anti-slagging chemical injection system must be installed.

Summation

Volumetric combustion created by Rotating Opposed Fired Air (ROFA) is a very effective method to perform large percentage direct co-firing of pretreated biomass and coal, and offers the possibility to utilise a large quantity of biomass at low investment cost.

Biomass pretreatment combined with modern combustion technology offers a new, effective way of using biomass for efficient, clean and low cost electricity production.

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